Efficient control schemes with limited computation complexity for Tomographic AO systems on VLTs and ELTs

C. Petit, T. Fusco, J.-M. Conan : ONERA
M. Le Louarn, P.-Y. Madec: ESO

ONERA
THE FRENCH AEROSPACE LAB

return on innovation

Overview

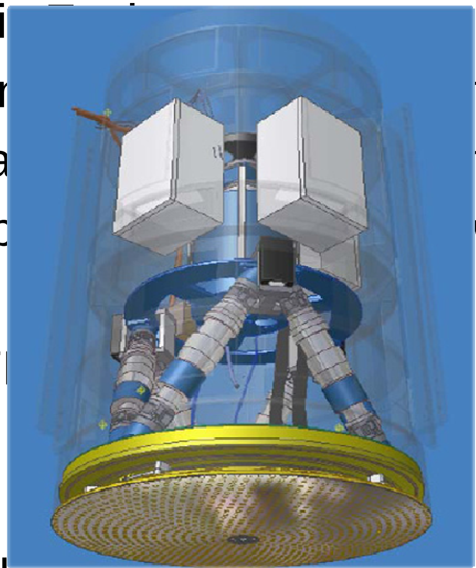
- Context: Tomographic AO for VLT and ELT
- Tomographic control solutions
- Simplifying Control Schemes into Single Matrix Vector Multiply
- Simulation Results
- Discussion & Perspectives

Tomographic AO for VLT

MUSE and its AO system GALACSI

Adaptive Optics Facility: Deformable Secondary Mirror (DSM) on 8m unit of VLT

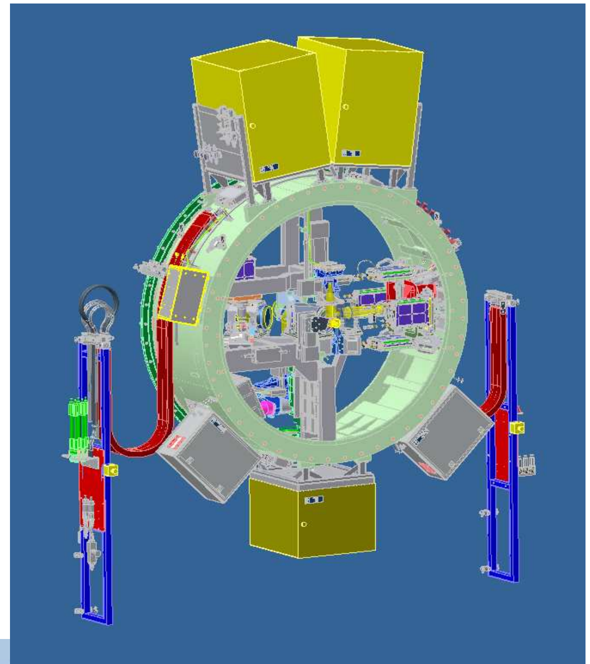
MUSE: Multi Unit Spectroscopi



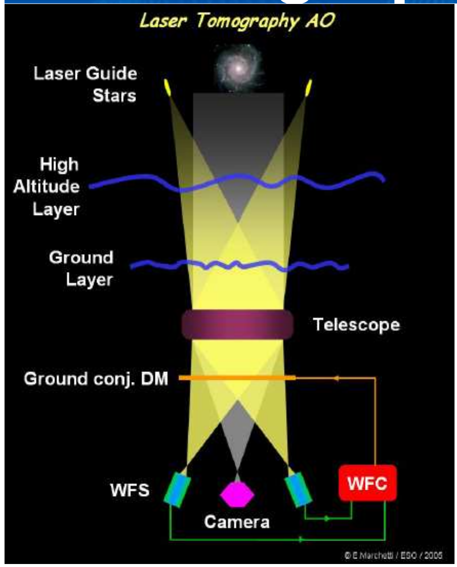
- 2nd generation instrumen field spectrograph in visible.
- Uses AOF, with Laser La n LGS)
- GLAO/LTAO correction p with DSM

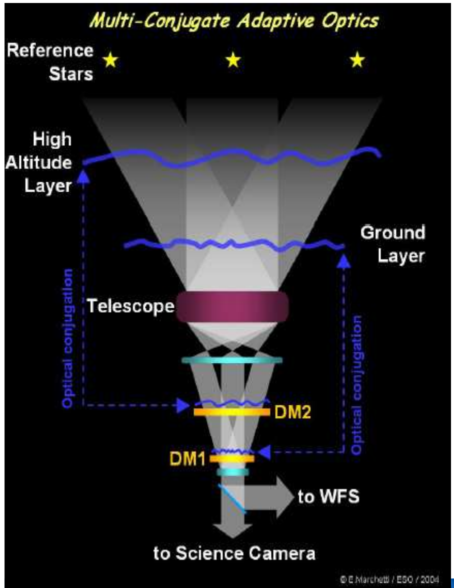
MUSE Narrow Field Mode (NF

- 7.5''x7.5'' FoV
- 4 LGS @10'' off axis
- 1 NGS for low order modes
- RTC: SPARTA platform -> Single MVM



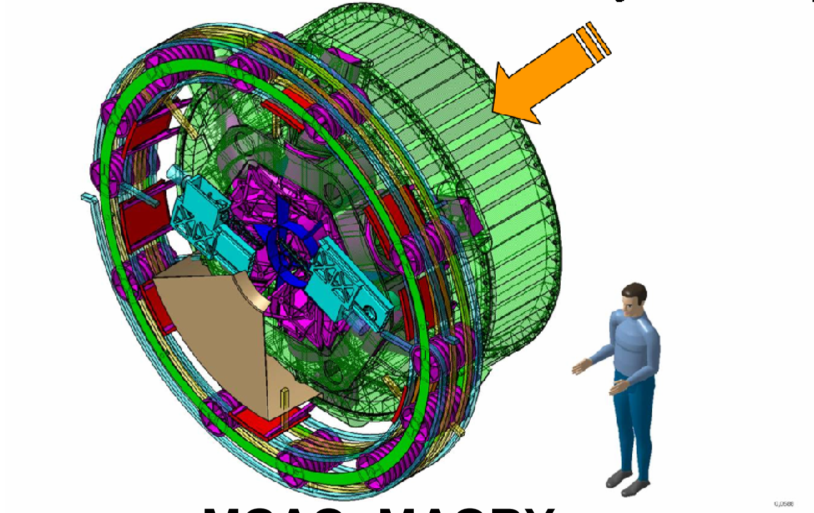
Tomographic AO for ELT

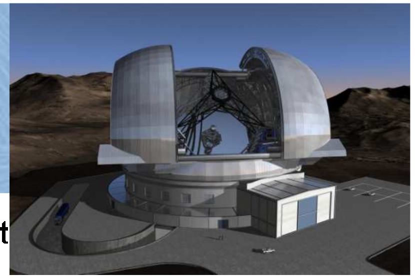




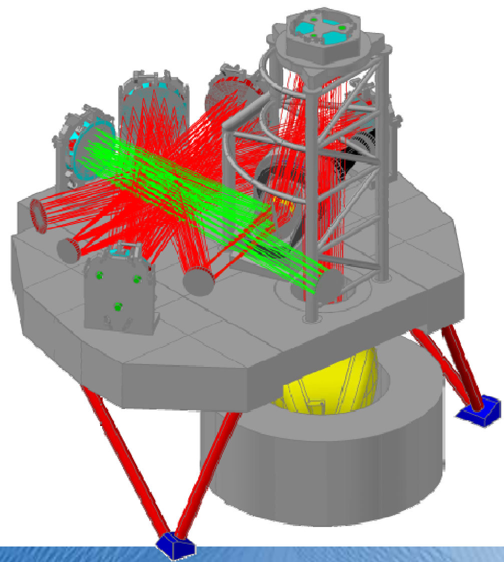
LTAO: ATLAS

Light from Nasmyth port





MCAO: MAORY

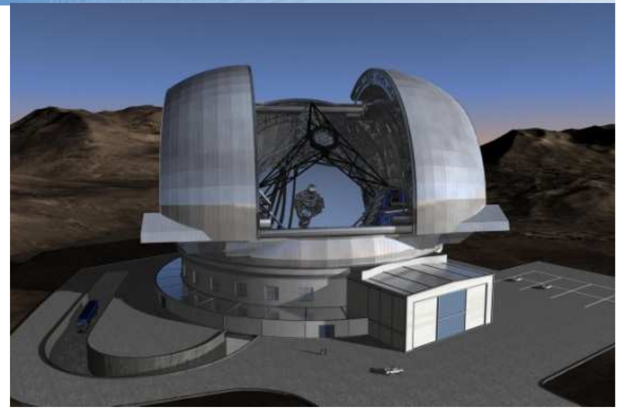


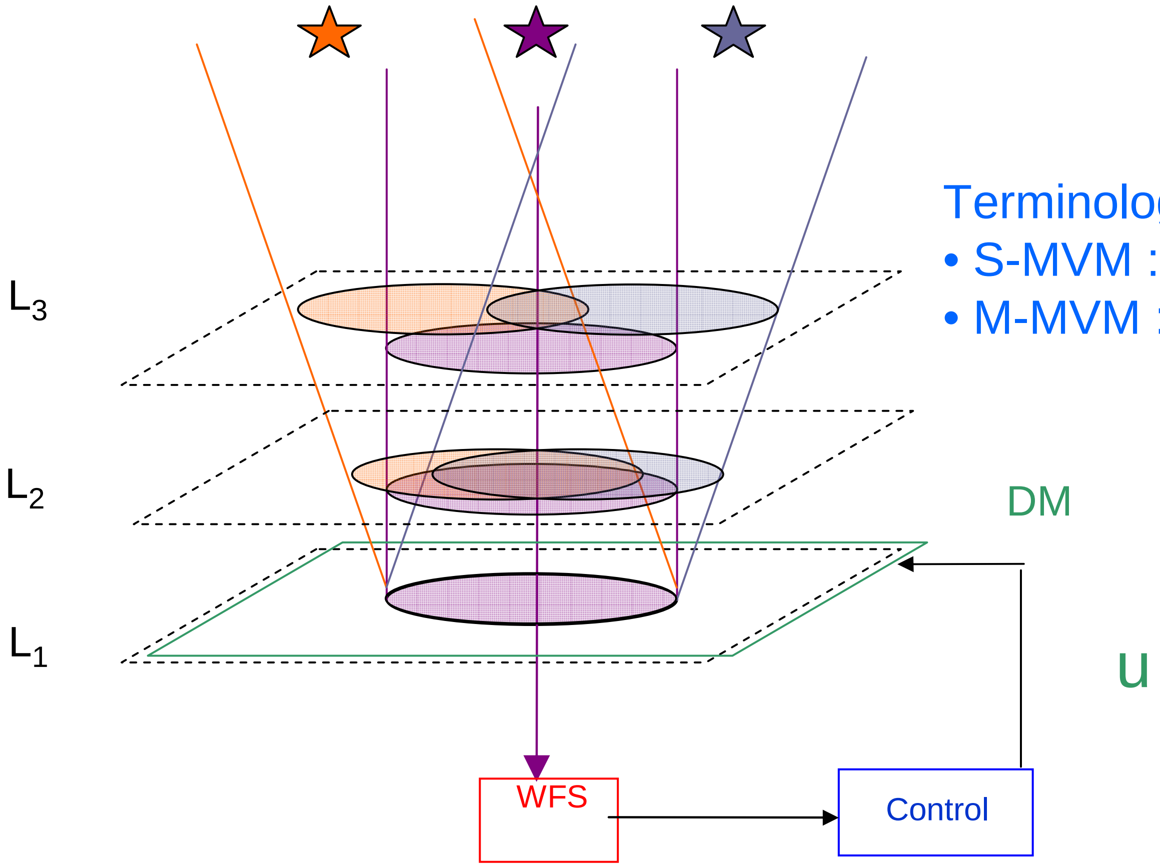
Tomographic AO control solutions

<u>Context:</u>

LTAO for VLT or ELT

→ Relies on tomographic control solutions.





Terminology :

- S-MVM : single matrix vector multiply
- M-MVM : multiple matrix vector multiply

Tomographic AO control solutions

- GLAO: generalized inverse of interaction matrix, integrator controller

$$u_k = u_{k-1} + R^{glao} y_k$$

→ S-MVM but No tomographic abilities, poor performance

- Virtual DM control

  reconstruction in the 2 layers into the 2 DMs from closed-loop data

  2 DM = actual ground DM + additional virtual DM in altitude

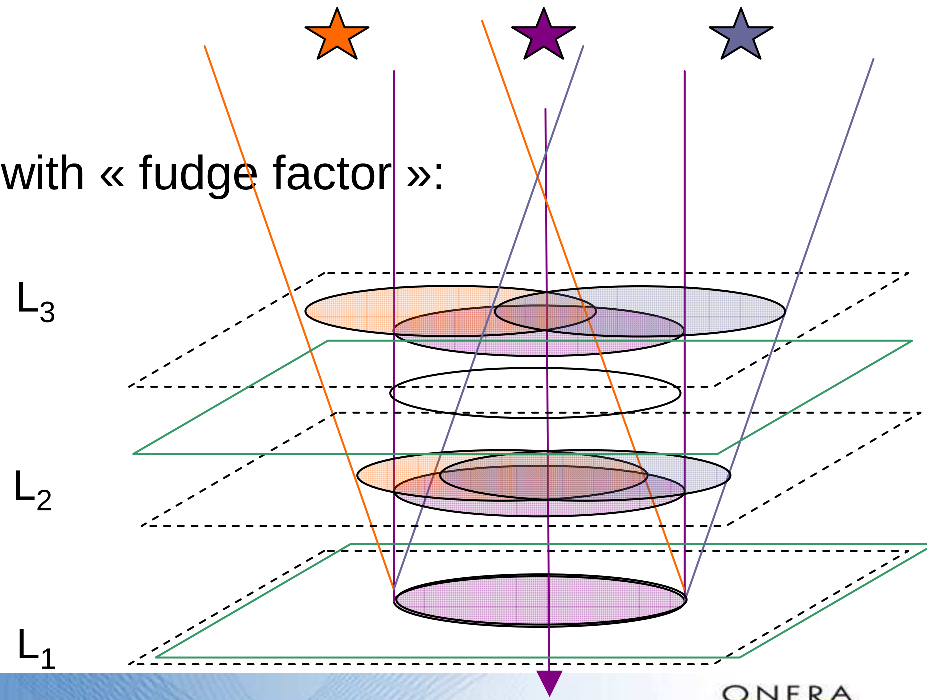
  + projection onto the real DM.

$$u_k = u_{k-1} + R^{vdm} y_k$$

R^{vdm} deduced from min. var. reconstructor with « fudge factor »:

$$W_{tomo}^{MV} = C_{kol} P_\alpha^T D^T \left(D P_\alpha C_{kol} P_\alpha^T D^T + \rho C_w \right)^{-1}$$

→ S-MVM. Sub-optimal. Tuning issues



Tomographic AO control solutions

- Pseudo Open Loop Control (POLC): static minimum variance reconstructor, applied on pseudo open-loop measurement + temporal filter:

$$\hat{\varphi}_{k+1} = \alpha\,\hat{\varphi}_k + \beta\,\hat{\varphi}_{k-1} + \delta e_{k-1} \qquad \text{and} \qquad u_k = P_{\beta=0}\hat{\varphi}_{k+1}$$

where:

$$e_{k-1} = W^{MV}_{tomo}(y_k + M^{\text{int}} u_{k-2}) - \hat{\varphi}_{k-1}$$

In another form:

$$u_k = \alpha\, u_{k-1} + \beta\, u_{k-2} + \delta P_{\beta=0} e_{k-1}$$

→ Tomographic reconstruction, M-MVM

- Linear Quadratic Gaussian: optimal solution according to minimum residual phase variance of the dynamic closed-loop control problem

$$\hat{\varphi}_{k+1/k} = A\hat{\varphi}_{k/k-1} + L_\infty(y_k - \hat{y}_{k/k-1}) \qquad \text{with} \qquad \hat{y}_{k/k-1} = D(P_\alpha \hat{\varphi}_{k-1/k-1} - N u_{k-2})$$

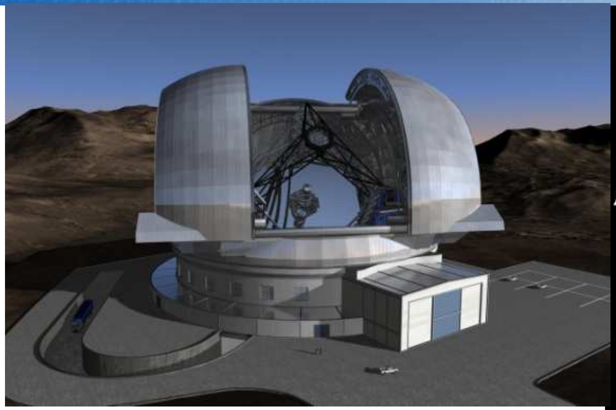
$$u_k = P_{\beta=0}\hat{\varphi}_{k+1/k}$$

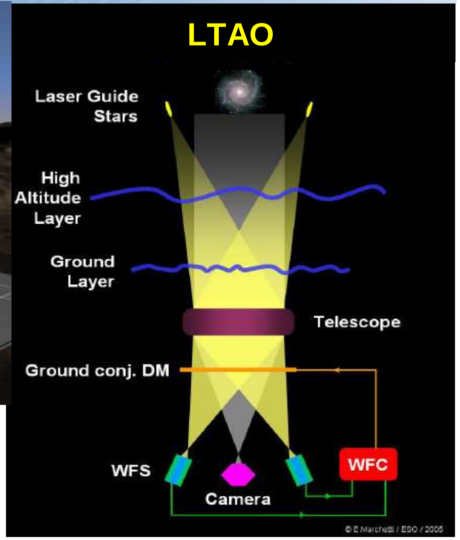
→ Optimal tomographic reconstruction and control. M-MVM

Tomographic AO control solutions

Context:

Tomographic AO for VLT or ELT





ATLAS

→ Relies on tomographic control solutions (vDM, POLC, LQG …).

→ Efficient solutions imply Multiple Matrix Vector Multiplications (M-MVM)

→ Question : Can we find a S-MVM control solution with good performance ?

- would fit in current RTCs such as SPARTA
- could limit the computation burden for ELT systems

LTAO on ELT (ATLAS) is 60000 slopes at 500Hz (1Gb/s input)

S-MVM control structure

Goal: propose a tomographic control solution for LTAO based on a S-MVM to reduce complexity/comply with RTC architecture of the type:

$$u_k = \alpha\, u_{k-1} + \beta\, u_{k-2} + \delta R y_k$$

Where y_k are measurements,

u_k are controls,

R is a matrix and α, β, δ scalar gains

Example: simplest possible R: inverse of interaction matrix -> GLAO

Simplified control scheme

<u>Objective:</u> « simplify » M-MVM control solutions (POLC, LQG) into S-MVM solutions

<u>Example with LQG:</u>

Basic equations

$$\hat{\varphi}_{k+1/k} = A\hat{\varphi}_{k/k-1} + L_\infty (y_k - \hat{y}_{k/k-1})$$

$$u_k = P\hat{\varphi}_{k+1/k}$$

In another way:

$$u_k = PA\hat{\varphi}_{k/k-1} + PL_\infty (y_k - \hat{y}_{k/k-1})$$

Obstacle to S-MVM:

permutation required   estimated measurement to be handled

Possible solutions:

- Permutation is possible: find *B* such as *BP* = *PA*

  B happens to be very close to $B \approx \alpha$ *Identity* $\rightarrow$ can be approx. by scalar gain.
- \+ Approximation : Estimated measurements taken as zero

<u>Either with POLC or LQG:</u> a S-MVM solution can be derived such that

$$u_k = \alpha\, u_{k-1} + \beta\, u_{k-2} + \delta R y_k$$

Simplified control scheme: discussion

Questions :
stability & performance of the DLQG and DPOLC in the form

$$u_k = \alpha\, u_{k-1} + \beta\, u_{k-2} + \delta R y_k$$

Control solutions derived with this approximations proves to be unstable:

- Approximations lead to α, β that do not satisfy stability constraints !
- In the end, these coefficients should be fixed wrt stability criterion
- Similarly to POLC approach (Gilles et al.) we set new coefficients so that :

$$\alpha + \beta < 1 \qquad \delta = 0.5$$

- Gain matrix *R* still derived from the initial control law (POLC or LQG)
  one can hope it preserves some good properties of original control

Simplified control scheme: performance

Case of study: end to end numerical simulation on LTAO system

(low order to speed-up calculations)

- 8 m telescope
- 3 or 10 layer turbulence profile, Cn^2 and wind profiles deduced from VLT profiles
- Good or poor seeing conditions (0.68'' or 0.95'')
- 4 Shack –Hartmann WFS, 8x8 sub. apert.

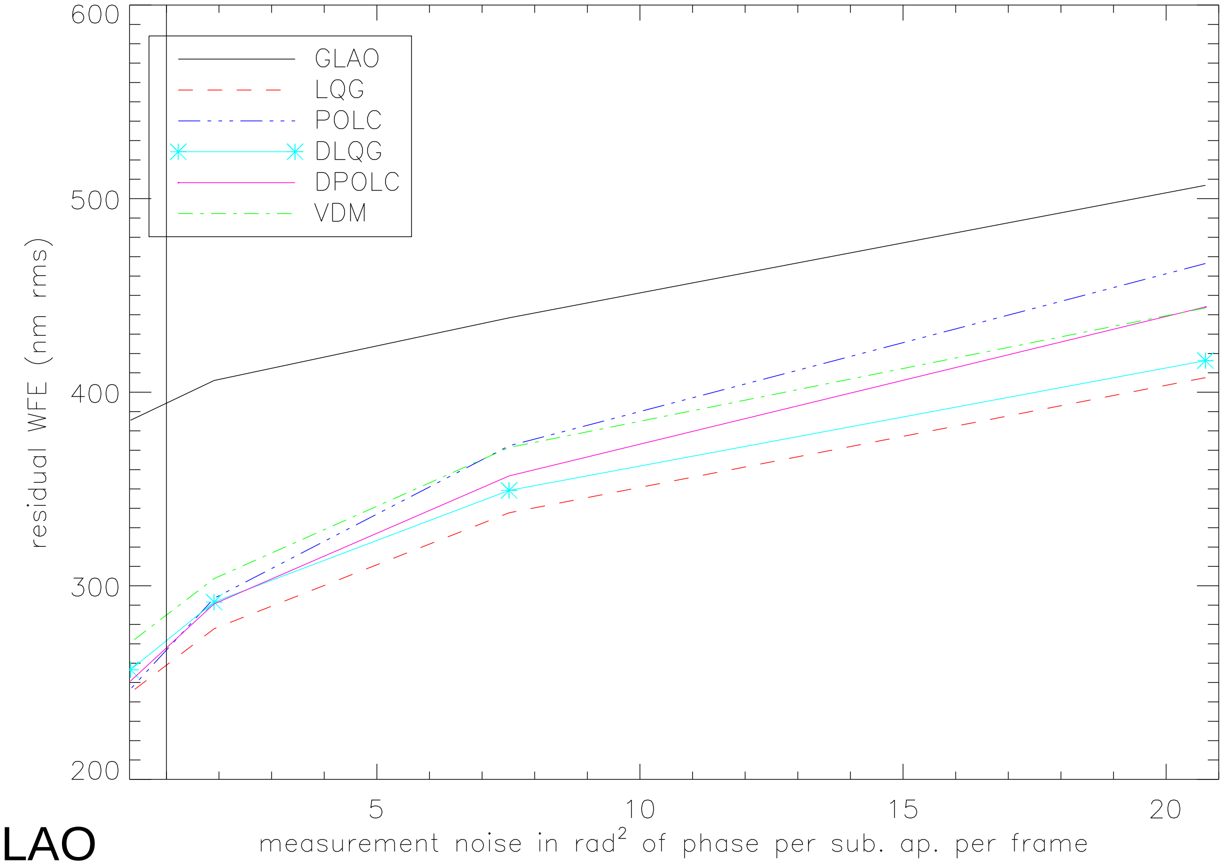
  + noise (photon noise regime)
- NGS at 30'' off-axis
- DM is 9x9 piezo stack 25% mech. coupling
- 500 Hz frame rate, 2 frame delay
- Analysis/correction @ 2.2µm

Compared performance versus noise level:

3 Layer profile

Similar result at

good and poor seeing



Observations:

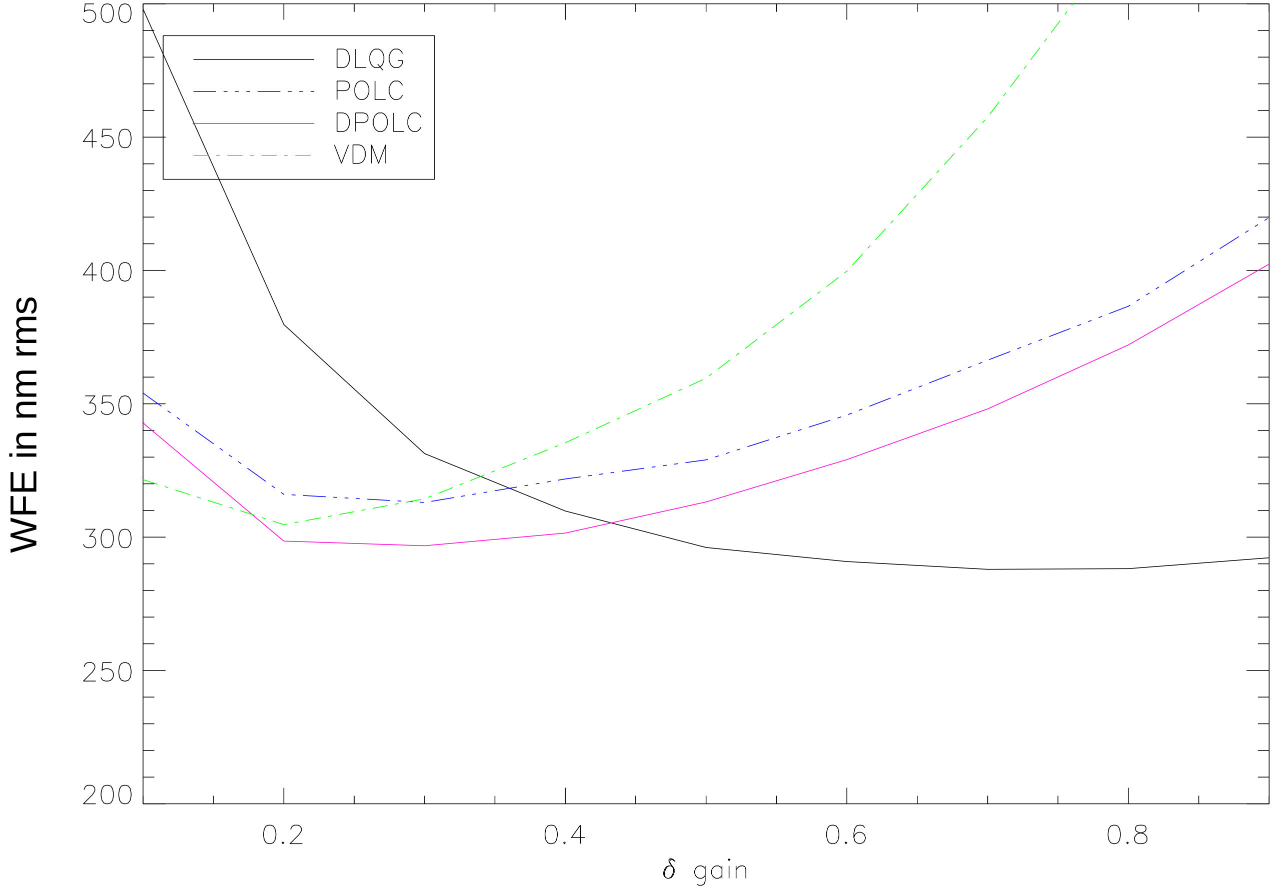
- Lowest performance is GLAO
- Optimal performance always provided by LQG
- POLC, DPOLC, LQG give same performance at high SNR
- DLQG, POLC and DPOLC provide intermediate performance between vDM and LQG, small advantage for Degraded LQG

Compared performance versus gain:

3 Layer profile

Similar result at

good and poor seeing



Observations:

- DLQG is less sensitive to the choice of the gain δ

Conclusions

- **S-MVM control algorithm have been derived from POLC or LQG**
- **Reduces on-line computation load**
- **Provides stable and efficient tomographic control**
- **Performance are in between vDM and optimal LQG**
- **Despite the drastic approx., DLQG keeps LQG good properties :**
  - better performance and smaller sensitivity to noise
  - robustness : not very sensitive to parameter tuning
- **Performance evaluation in MUSE configuration are planned**

  on Octopus @ ESO

Trade-off optimality – computation cost

Without being as extreme as S-MVM :

- ❑ **Use similar approximation to derive a M-MVM LQG in the voltage space**

  would allow reconstruction on many layers [Costille et al., this conference]

  with no increase of real time burden

  (nice property of POLC in voltage space)

- ❑ **Go for Sparse iterative methods and avoid solving Riccati equation**
  - ❑ Kalman gain deduced from physical considerations [Correia AO4ELT 2009]
  - ❑ Ensemble Kalman Filter [see Morgan Gray (LAM) this conference]

- ❑ **Exploit spatial invariance of the problem**

  ultra-fast Kalman gain computation based on spatial invariance

  & reduction of real-time calculations

  [Paolo Massioni JOSA A 2011 accepted]

- ❑ **Keep an eye on properties of interest**

  performance (temporal + noise + tomography(…) errors), robustness